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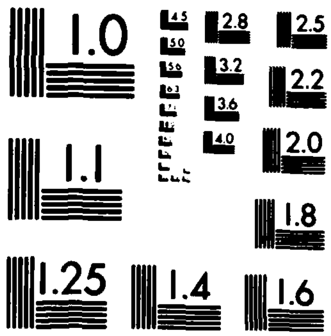

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THE ACCESS OF ENERGETIC CHARGED PARTICLES TO SATELLITE ALTITUDES

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Primary cosmic ray particles are able to arrive at earth satellites, orbiting at altitudes of only a few hundred kilometres, from zenith angles considerably larger than that of the local horizon. The largest zenith angles at which below horizon access is possible have been investigated for a series of satellite altitudes between 400 km and 3600 km. The largest accessible zenith angle found at 400 km is 150°. The angle becomes larger with increasing altitude, reaching 180°, (the nadir direction) at 1250 km. Particles arrive at these large zenith angles from a range of westerly directions.

At altitudes above 1250 km, particles passing beneath the satellite with their paths curving upwards are able to arrive at large zenith angles from easterly directions. The ranges of zeniths and azimuths involved are altitude dependent.

Largest zenith angles of arrival can be interpolated between azimuths, in limited azimuthal ranges only. These ranges are centred about the azimuth (270 - latitude)°. The range of reliable interpolation is altitude dependent, becoming larger at higher altitudes. (deg)

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1. Introduction.

The ability of energetic charged cosmic-ray particles to arrive at a particular location within the magnetosphere can be characterised by the cutoff rigidity for the location and the direction of particle arrival. Knowledge of the cutoff rigidity is a pre-requisite for the determination of the total radiation dose from such particles at the location from the direction under consideration. Calculation of cutoffs is a time consuming task, which can be expedited by prior knowledge of the directions from which primary particles of any rigidity are able to reach a specific location.

The general aim of the research reported here was to extend the information previously available on the access of cosmic rays to Earth orbiting spacecraft, at altitudes between a few hundred and a few thousand kilometres. This range encompasses the locations encountered by all but the lowest orbit satellites having periods of a few hours or less. There were several specific aims within the general heading. Particular attention was to be paid to below-horizon directions of arrival; to estimates of the effect due to the proximity of the solid Earth; and to attempts to identify locations and altitudes at or near which interpolation between cutoffs calculated for adjacent locations and/or directions of arrival does not produce usefully accurate results. It was also planned to start to investigate the sensitivity of the calculated results to the various available models of the geomagnetic field, and to assumptions made in connection with the effect of the atmosphere.

2. The effect of altitude on access from below-horizon directions.

Directions from which at least some particles are able to arrive at a given location may in principle be determined by the use of a brute force method similar to that needed for explicit calculation of cutoffs. A very large computational effort is required to produce the necessary 5-dimensional matrix of values using the standard trajectory-tracing technique. The variables involved are the location (latitude, longitude, and altitude), and the particle's direction of arrival, expressed in terms of azimuth and zenith angles. It was, therefore, never intended that the project should be undertaken in that manner.

An alternative way to approach such a survey is to consider a particular location and azimuth of arrival, and to then search for the largest possible zenith angle at which the location may be reached by an incoming primary cosmic ray particle. A technique was devised to search rigidity/zenith-angle space for accessible arrival directions (Humble et al, 1983, attached as Appendix B). The search proceeds, for a given location and azimuth, in the directions of increasing zenith angle and decreasing rigidity, until no further accessible directions of arrival can be found.

Each search was started at a zenith angle of 100°, above the local satellite/Earth horizon at all altitudes considered (Humble, 1983, attached as Appendix B; Table 1). It was found that, for zenith angles larger than that of the horizon, primary particles are only able to reach the satellite from generally westerly directions. Such particles experience a $\underline{V} \times \underline{B}$ force having a positive radial component in the final stages of their approach to the satellite. Their trajectories consequently have positive upwards curvature, and the local zenith angle of arrival can be larger than that of the horizon. The range of accessible azimuths increases with altitude, as would be expected.

In general, it would be expected that the largest accessible zenith angle for a given latitude, longitude, and azimuth, would also increase with increasing altitude. This was found to be the case. Defining Z to denote the largest accessible zenith angle found at any altitude, regardless of latitude, longitude, or azimuth, the following results were obtained:

Altitude	Z
400 km	150°
600	156
800	166
1000	172
1250	180

More detailed results are given in the two publications which have so far arisen from this work (Humble et al, 1983: Appendix A; Humble, 1983: Appendix B).

Note that a Z of 180° for a particular altitude means that primary particles are able to reach a satellite at that altitude from the nadir direction, directly underneath it, at at least one location somewhere on the orbit. This does not, however, mean that all possible directions of arrival are accessible at such a location. Easterly arrival directions at below-horizon zeniths are still forbidden.

As the altitude increases above 1250 km a range of large zenith angles in generally easterly directions begins to become accessible, whilst smaller (but still below-horizon) zenith angles in the same azimuthal directions remain inaccessible. The higher altitude permits particles approaching the general region of the satellite at low altitudes from the west to pass above the top of the atmosphere more than one gyro-radius beneath the satellite. Such particles will arrive at the satellite from easterly directions at large zenith angles.

The phrase "generally easterly" used above requires qualification. The precise azimuths at which these effects occur are latitude dependent. The largest zenith angles of access occur in directions which are slightly equatorward of west in both hemispheres. The curve-under effect occurs in the set of opposite directions, slightly to the poleward of east in both hemispheres.

Preliminary surveys were conducted at altitudes of 2400 and 3600 km. These computations, like all others in this study, were performed for 20° intervals in latitude and 60° intervals in longitude. At 2400 km the curve-under phenomenum was found to exist only at latitudes between 20°N and 20°S. At these latitudes the effect is also markedly longitude dependent, due to the asymmetric nature of the geomagnetic field. Accessible easterly zenith angles were found to commence at the nadir, zenith angle 180°, and to extend to zenith angles of about 140°, with a couple of cases running up to 110°, well above the satellite/Earth horizon at this altitude.

Similar results were obtained for 3600 km altitude, except that the range of allowed easterly zeniths is much larger and the latitude range extends to 40° in both hemispheres. The longitude effect is not so noticeable. Furthermore, a considerable number of cases were found at this altitude for which some easterly azimuths are accessible at all zenith angles. In these cases the range of zeniths accessible by particles from the west looping below the satellite overlaps the range accessible by particles of other rigidities approaching more directly from the east. Due to the nature of the search algorithm employed, it is suspected that a few more such cases may exist than have actually been detected. Detailed checking in a few directions suggests that the algorithm probably detects at least 90% of the occurrences.

3. The Interpolation Problem.

The results obtained in the course of the above calculations show that there are some regions and directions at which simple interpolation of cutoffs between adjacent directions and/or locations is able to produce usefully accurate results, whilst at other directions/locations this is not so. In general, cutoff interpolation in below-horizon directions is practicable at those directions and locations at which the gradient of the maximum accessible zenith vs. azimuth curve (Humble,1983: Appendix B; Figure 1) is moderate. Useful interpolation is impracticable wherever that curve is steep, since discontinuities in maximum accessible zenith angle occur quite frequently in that situation. The discontinuities are due to the increasing or decreasing of the influence of particular components of the geomagnetic field as azimuth of arrival changes.

The accuracy of the interpolation process varies both with altitude and with azimuthal direction. The most reliable values can be obtained between azimuths of 195° and 345° at 3600 km altitude, reducing to a rather smaller azimuthal range, of about 90°, at 400 km. This range is centred about directions which are approximately (270 - latitude)°, significantly to the equatorward of west at all but the lowest latitudes.

4. Comparison of Geomagnetic Field Models.

The present project is based on, and has made use of some results from, work performed previously. That work used the then best available numerical model of the internal geomagnetic field, being an 8th order model based on a 1975 field model extrapolated forward to epoch 1980.0 by use of associated secular drift coefficients. It was known at that time that this model was not ideal, and that more accurate models would shortly become available.

About the time the present project commenced a 10th order definitive International Geomagnetic Reference Field for epoch 1980.0 was published. Accessibility calculations were immediately performed for selected locations using this field model, in order to assess the sensitivity of the results to the choice of field, and to determine if it would be necessary to recalculate any or all of the results previously obtained. The 10th order field model requires the use of approximately 25% more computer time than do the 8th order models, and comparative calculations were therefore also performed using the 10th order field arbitrarily truncated to 8th order. The sensitivity of the results to the choice of field model was found to be location dependent, being most noticeable in the South Atlantic and South American regions (Humble et al, 1984). (This paper, which is attached as appendix C, reports an amalgamation of work carried out under the present contract and related work performed separately by AFGL staff). The sensitivity in other regions is not so strong, and it was not deemed necessary to recalculate many of the previous results.

5. The effect of the atmosphere.

This aspect of the project was directed towards determining the effect on the results of the use of a realistic model atmosphere to determine cosmic-ray absorption, rather than making use of the standard assumption that the atmosphere is completely opaque to any primary particle which descends below an altitude of 30 km. Only very preliminary calculations were completed, amounting to little more than the necessary checking of the computer programmes involved. The few available results appear to indicate that the 30 km limit is a sensible approximation. This result had been anticipated; however, considerably more work will be required before any definitive conclusions can be drawn from this aspect of the project.

6. Publications.

Humble, J. E., D. F. Smart, and M. A. Shea, "Cosmic Ray Access to Satellites from Large Zenith Angles", 18th International Cosmic Ray Conference, Bangalore, Conference Papers, 3, 442-445, 1983. (AFGL-TR-83-0296)

Humble, J. E., "On Directions from which Cosmic Rays may reach Earth Satellites", Proc. Astron. Soc. of Australia, 5, 265-267, 1983. (AFGL-TR-84-0251)

Humble, J. E., M. A. Shea, and D. F. Smart, "Sensitivity of Cosmic Ray Trajectory Calculations to Geomagnetic Field Model Representations", Phys. of the Earth and Planetary Interiors, in press.

Copies of the above papers are attached (Appendices A,B,C).

7. Scientific Presentions.

Humble, J. E., D. F. Smart, and M. A. Shea, "Hits Below the Belt - Cosmic Ray Direct Access to Low Altitude Satellites from Earthward Directions", 1982 Fall meeting of the American Geophysical Union, San Francisco, CA., December 1982. Abstract published in EOS, Transactions, AGU, Vol. 63, No. 45, p. 1055, November 9, 1982.

Humble, J. E., "The Directions from which Cosmic Rays May Reach Earth Satellites", Annual Meeting of the Astronomical Society of Australia, Sydney, N.S.W., Australia, May 1983.

Humble, J. E., "Field Model Comparisons: Cosmic Ray Differences between the Predicted and Adopted 1980.0 Fields", XVIII International Union of Geodesy and Geophysics, International Association for Geomagnetism and Aeronomy General Assembly, Hamburg, FRG, August 1983.

Humble, J. E., D. F. Smart, and M. A. Shea, "Cosmic Ray Access to Satellites from Large Zenith Angles", 18th International Cosmic Ray Conference, Bangalore, India, August 1983.

Humble, J. E., "Cosmic Ray Access to Spacecraft from Earthward Directions: The Role of the Atmosphere", Annual Meeting of the Astronomical Society of Australia, Coonabarabran, N.S.W., Australia, May 1984.

Abstracts of the above presentations are attached (Appendix D).

APPENDIX A.

COSMIC RAY ACCESS TO SATELLITES FROM LARGE ZENITH ANGLES

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ABSTRACT

As the altitude of earth-orbiting satellites increases it becomes progressively easier for primary cosmic-ray particles to gain access to them from directions below the geometric horizon. Results are presented from a comprehensive survey of the largest accessible zenith angles for a range of altitudes and geographic locations. The search has disclosed that primary particles are able to reach a satellite at an altitude of 1250 km from zenith angles as large as 178°.

1. Introduction

Some interest has been expressed in recent times in the ability of primary cosmic-ray particles to reach satellites in low altitude earth-orbit from directions below the local horizon. At the Paris Cosmic Ray Conference, Humble et al. (1981) showed that primary particles are able to reach a satellite at a zenith angle of 120° from a range of western azimuths at all the geographic locations which were investigated. The calculations were substantiated by the results of experiments on board the HEAO-C satellite (N.Lund, private communication 1981). The investigation reported here extends these studies by determining in a systematic fashion the largest zenith angles accessible to primary particles at a selected range of azimuths and set of satellite altitudes and locations.

Calculations are reported for altitudes of 400, 800 and 1250 km, for latitudes at 20° intervals from 40°N to 40°S at each altitude, and longitudes at 60° intervals starting at 0° at each latitude. For each location thus defined a suitable range of azimuths likely to be accessible to primary particles at zenith angles of 120° or larger (Humble et al., 1981) was investigated.

2. Method

The calculations have been carried out using the standard trajectory calculation program (Shea et al.,1965). For continuity with earlier work we have continued using the former International Geomagnetic Reference Field for 1980.0, as extrapolated from IGRF 1975.0 with the use of secular correction coefficients (IAGA Study Group,1976). We note that future calculations should use the new definitive ICRF 1980.0 model resulting from the Edinburgh meeting of IAGA (Peddie,1982).

As zenith angles increase at a particular location and azimuth of arrival the Horizon Limited Rigidity* necessarily decreases, due to the increased curvature required for the final stage of the trajectory (Humble et al.,1981). A similar situation holds true for particular penumbral bands. The rather simple minded, but effective, search technique used was, therefore, to commence calculations at zenith angle 120° and a large rigidity, usually around 30 GV. If this trajectory was allowed the zenith angle was incremented by 2° whilst if it was forbidden the rigidity was decremented by 1%. The process was then repeated at the new zenith or rigidity.

The technique is fast, in that the majority of the trajectories involved are simple ones. It has the effect of following particular penumbral features through increasing zenith angles. If one such band ends as zenith angle increases the next lowest (in rigidity space) band is automatically found. This process continues until the Stormer cone is encountered. The technique does ignore the possibility that a penumbral allowed band may exist at relatively high rigidities extending to larger zenith angles than do the lower rigidity bands first explored. One or two such examples have been found, the clear implication being that great care must be used in selecting the starting rigidity.

3. Results and Discussion

The largest accessible zenith angles, Z, found at each location are listed below.

Altitude	Longitude	0	60	120	180	240	300
400 km	40 N	144	142	142	144	138	136
	20 N	140	140	138	136	144	148
	0	138	138	140	138	138	138
	20 S	136	142	144	144	136	136
	40 S	136	136	130	138	146	140
800 km	40 N	156	154	156	156	148	146
	20 N	164	160	160	160	164	162
	0	158	160	160	160	158	162
	20 S	156	156	158	166	160	156
	40 S	146	146	140	148	158	158
1250 km	40 N	162	162	162	162	156	152
	20 N	178	178	176	178	172	168
	0	172	174	174	176	176	178
	20 S	166	164	166	174	174	170
	40 S	154	154	148	154	164	170

*The highest rigidity with which primary particles can reach the site. This was called "Allowed Rigidity" in our 1981 paper; we believe the present name to be more descriptive.

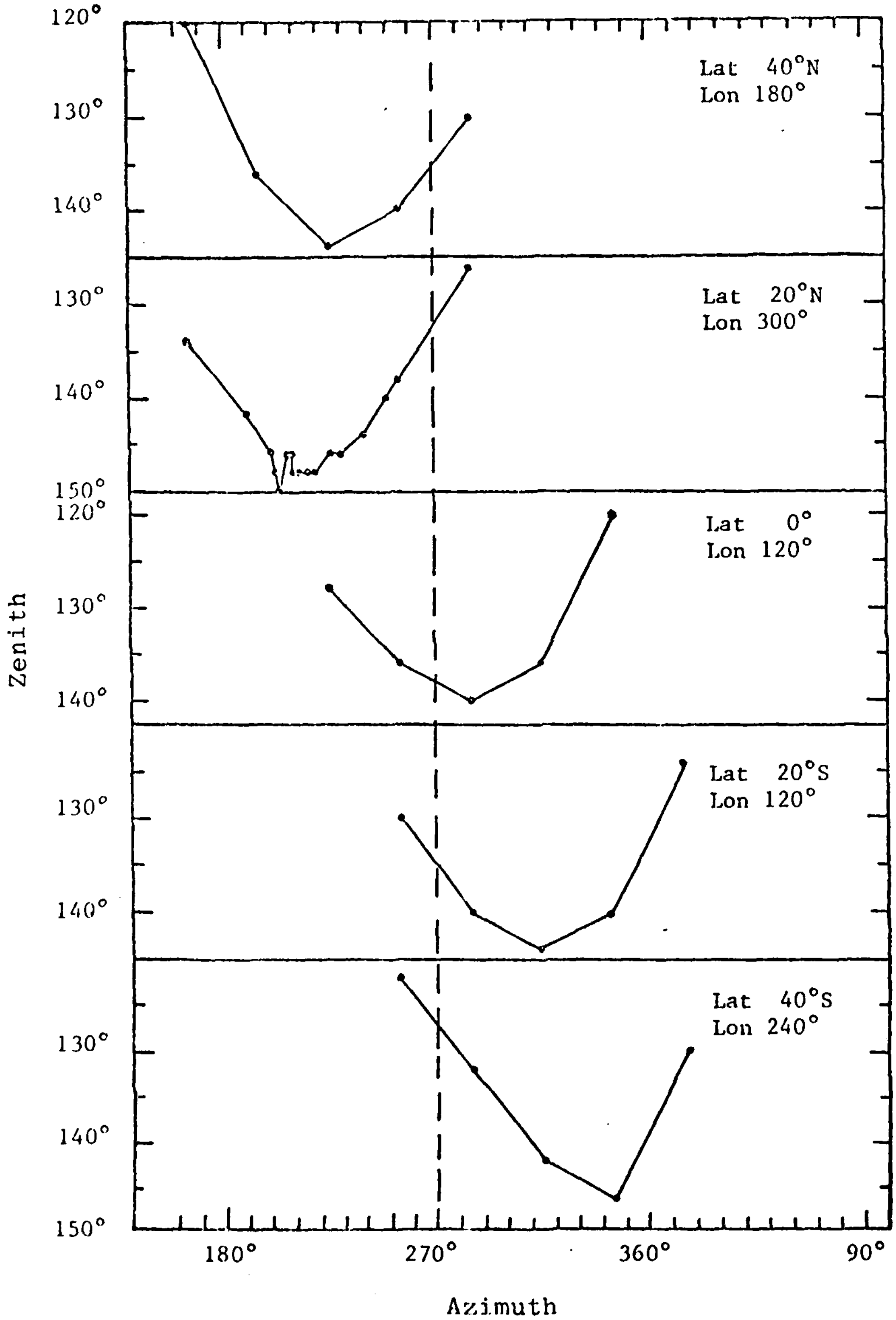
120°
130°
140°
Lat 40°N
Lon 180°
130°
140°
150°
Lat 20°N
Lon 300°
120°
130°
140°
Lat 0°
Lon 120°
Zenith
130°
140°
Lat 20°S
Lon 120°
130°
140°
150°
Lat 40°S
Lon 240°
180°
270°
360°
90°
Azimuth

Figure 1 shows scans of the largest accessible zenith angles found versus azimuth, for one site at each latitude at 400 km altitude. Note that the largest zenith angle accessible at each site occurs at azimuths to the equatorward of West. This is true in all cases which we have investigated. Note also the fine details plotted for 20°N 300°. Extensive calculations were undertaken at this site.

The distribution of Z with latitude varies according to the altitude involved. At 400 km there is no detectable relationship between Z and latitude. However, a relationship begins to be apparent at 800 km, and is much more obvious at 1250 km, at which altitude the largest values of Z are found between 20°N and 20°S. The Z values at higher latitudes are noticeably reduced.

The largest values of Z found at each altitude, and indicated in the table, are 148° at 400 km, 166° at 800 km, and 178° at 1250 km. These compare with horizon zenith angles of 110, 117, and 123° respectively. The listings only indicate values actually found at a selected grid of locations. They do not exclude the possibility of larger values being found at non-grid locations. The limited spot checks which we have made at 400 km only, for various latitudes between 40°N and 20°S have revealed one such case, an allowed trajectory at a zenith angle of 150°. Due to the method used we cannot completely guarantee that larger angles than those listed also exist at the grid locations. However, we believe that significant variations are unlikely.

It should also be noted that the calculations are artificial in one important respect. They assume, along with earlier calculations, that all particles descending below a local altitude of 30 km undergo interaction with the atmosphere. The general agreement referred to earlier between the HEAO-C observations and early calculations for 400 km altitude suggest that the assumption may be reasonable, but the point requires elucidation.

Acknowledgements

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Shea M A, Smart D F and McCracken K G - A study of vertically incident cosmic ray trajectories in a sixth degree simulation of the geomagnetic field. J.Geophys.Res. 70, 4117 (1965)

APPENDIX B.

$$A = (\Delta I/I_0)_{\mathrm{Underground}} - 0.14\,(\Delta I/I_0)_{\mathrm{Neutron}}$$

Where ΔI is the deviation of the daily average intensity I from a reference intensity I_0. The latter was chosen as the value of daily average intensity on 11 July, one day before the commencement of the decrease.

The A variations are shown in Figure 2(c). They exhibit a prominent 27-day periodicity, clearly not initiated by the Forbush Decrease. It seemed that the variations might be due to the interplanetary North-South anisotropy for which firm evidence has emerged during the last decade (Swinson, 1971). this is a $\mathbf{B} \times \nabla(n)$ phenomenon, where $\mathbf{B}$ is the interplanetary magnetic field (IMF) vector and $\nabla(n)$ is the density gradient vector of cosmic ray particles, directed radially outward from the Sun. The resulting particle drift normal to the plane of the ecliptic produces a diurnal variation of intensity (in sidereal time) and a daily average intensity term. It is the latter, known as the North-South (N-S) asymmetry, that is of interest here.

The N-S intensity $I(\delta)$, at a latitude δ, varies as $\sin \delta$. Thus it is asymmetric with respect to the hemisphere of observation, an increase in one hemisphere being mirrored by a decrease in the other and vice versa. Moreover, the asymmetry reverses direction with reversals of direction of the sectorised field vector $\mathbf{B}$. It has a flat, $\sim P_{M}^{0}$, rigidity spectrum. The magnitude of the asymmetry, at mid-latitudes of observation, is usually small, being $\sim 0.1\%$. Thus it can easily be swamped by large isotropic variations.

Until now, only the large multi-directional telescope system at Nagoya, Japan, has been able to detect the N-S asymmetry with sufficient accuracy for day-to-day variations to be observed. Isotropic effects are removed by recording the difference of intensity between north-pointing and south-pointing (equatorial scan) telescope components. The daily difference measurements, known as GG, have been observed to follow a 27-day variation, within which the peaks tend to correspond with the Towards direction of the sectorised IMF and the troughs with the Away direction. This expected correspondence has been achieved on more than 70% of daily occasions over several years of observation (Mori and Nagashima 1979).

In Figure 2(c) the variations of GG, inverted because of the latitude asymmetry, are compared with the variations of A. It is clear from the close agreement between them (linear correlation coefficient $r = 0.62$) that the systematic variations of GG and A are due to the same phenomenon. That they are due to the N-S asymmetry can be seen from the striking correspondence of the peaks and troughs of the variations with the Away and Towards polarities of the IMF (Figure 2(d)).

Conclusion

The most promising feature of these initial results, achieved by quite different methods in the two hemispheres, is the fidelity with which the variations from Nagoya and Mawson have tracked each other, not only over the period shown, but in succeeding months. It means that a sufficiently high degree of stability of observation has been attained as to enable, for the first time, various kinds of long-term trends in the average intensity underground to be investigated in both hemispheres and, further, differences in trends between the hemispheres, for which there is already some evidence in the observations reported here.

The generous cooperation of Professor K. Nagashima (Director), Professor K. Murakami and Dr Z. Fujii of the Cosmic Ray Research Laboratory, Nagoya University, who assisted with the arrangements for purchasing the proportional counters and with the design of the counter units and who provided the Nagoya GG data, is gratefully acknowledged.

The authors also wish to thank Mr J. Cooper, who was in charge of the Mawson observatory in 1982, for his skilled construction of the framework and for the installation of the telescope underground.

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On Directions from which Cosmic Rays may Reach Earth Satellites

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Introduction

It is easy to feel, on an intuitive basis, that primary cosmic rays of at least some energy range will be able to reach a satellite in earth-orbit from all directions above the local geometric horizon and from essentially no directions below the horizon. This argument suggests that directional cosmic ray detectors on board satellites may safely assume that the only particles received from earthward directions must be splash or albedo particles from the atmosphere, and that any equipment liable to possible radiation damage should be preferentially located on the earthward side of the satellite. In actual fact primary cosmic rays can have quite sharply curved trajectories in the magnetosphere, thereby enabling some particles to gain access to a satellite from a range of directions below the local geometric horizon. The present work presents recent quantitative results on this matter.

The Calculations

Calculations have been carried out using the standard computer program for computing cosmic ray trajectories in the magnetosphere (Shea *et al.* 1965). For continuity with earlier work the former International Geomagnetic Reference Field for 1980.0, as extrapolated from IGRF 1975.0 by use of secular correction coefficients (IAGA Study Group 1976) has been used. The differences caused by the use of this model of the geomagnetic field rather than the more recently published definitive IGRF 1980.0 model (Peddie 1982) will be the subject of further investigation. Preliminary computations suggest that the differences will not be large.

The procedure adopted is to calculate, by numerical integration of the equations of motion, the trajectory of a negatively charged particle leaving the satellite in a specified direction. This trajectory will be precisely the same as, but traversed in the opposite direction to, that of a positively charged particle arriving at the satellite from the specified direction. If the trajectory of the negative particle enters the atmosphere, at an altitude of 30 km or less above mean sea-level, it is unlikely that an inbound positive particle would emerge from the atmosphere in that particular direction, since it would have been destroyed in interactions with atmosphere particles before doing so. The particular direction of arrival is, therefore, considered to be forbidden to incoming particles. The argument is stronger yet in the event that the trajectory intersects the solid earth.

The only significant force acting on the cosmic ray particles in the magnetosphere is $\mathbf{v} \times \mathbf{B}$, and it is obvious that the only particles able to reach the satellite from directions below the local horizon are those for which $\mathbf{v} \times \mathbf{B}$ has a positive radial component in regions close to the satellite. Broadly, this will tend to facilitate access from below horizon zenith angles for particles arriving from westerly azimuths (Humble *et al.* 1981), whilst inhibiting such access from generally easterly directions.

Results

Calculations of this type produce a plethora of results encumbered with a number of parameters. The specific variables are the location (latitude, longitude and altitude) of the satellite and the magnetic rigidity and direction of arrival (expressed in terms of zenith and azimuth angles) of the particle whose trajectory is being investigated. The present calculations have been directed towards finding the largest zenith angles with which primary cosmic ray particles can reach the satellite at each of a range of locations. Searches for such large accessible zenith angles have been carried out at locations specified by all possible combinations of latitude at 20° intervals from 40°N to 40°S inclusive, longitude at 60° intervals starting at 0°, and altitudes of 400, 800 and 1250 km above the mean spherical earth. A smaller range of latitudes has also been investigated at altitudes of 600 and 1000 km. Some additional azimuths were also investigated at 400 km altitude, with the aim of detecting any fine scale dependence of largest accessible zenith angle with azimuth.

Table 1

Variation of Largest Accessible Zenith Angle with Altitude

Satellite Altitude (km)	Zenith Angle of Horizon (deg)	Largest Accessible Zenith Angle (deg)	Latitude (deg)	Corresponding Longitude (deg)	Azimuth (deg)	Rigidity (GV)
400	110	150	20 N	300	204#	5.096
600*	114	156	20 N	300	195	6.535
800	117	166	20 S	180	345	8.216
1000*	120	172	20 N	0	255	8.897
			20 N	60	255	10.432
1250	123	180	20 N	0	195	9.444
			20 N	0	255	9.444

*Searches performed at latitudes 40°N, 20°N and 0° only.

#A computationally non-standard azimuth. The largest accessible zenith angle found at 400 km at a standard azimuth was 148°.

Table 2

The variation of largest accessible zenith angle with geographic location at 400 km altitude.

Latitude	Longitude 0	60	120	180	240	300
40 N	144	142	142	144	138	136
20 N	140	140	138	136	144	150
0	138	138	140	138	138	138
20 S	136	142	144	144	136	136
40 S	136	136	130	138	146	140

At each location searches have been carried out at 30° azimuth intervals, ranging larger or smaller as required from 255°. These generally westerly directions are those previously mentioned for which $\mathbf{v} \times \mathbf{B}$ is known to have a positive radial component in the region of the satellite. The risk that the use of azimuths so pre-determined might lead to a self-fulfilling prophecy in the final results was avoided by taking care to extend most of the searches in azimuth until it was evident that no further possibility of access at large zenith angles remained.

The largest accessible zenith angles found at each altitude, regardless of satellite geographic position or of particle azimuth of arrival, are shown in Table 1. It can be seen that the increase in the angle with altitude is essentially linear, to within the coarseness (2°) of the zenith steps used.

The programme used to obtain the above results makes a complete set of calculations for any specified location and azimuth of particle arrival. For each set of initial conditions it searches rigidity-zenith space for the largest zenith angle for which primary cosmic ray access can be confirmed. The algorithm used (Humble *et al.* 1983) is satisfied by finding a single allowed trajectory at a further, larger, zenith. Consequently, the rigidity of the particle for which an allowed trajectory is found is only a pseudo randomly chosen member of the set of rigidities with which particles may be able to arrive at the satellite from the direction under consideration. It is necessary to recognise this restriction when considering the rigidities quoted in the final column of Table 1.

There are considerable variations between the largest accessible zenith angles found for individual longitudes at any given latitude and altitude. The results in Table 2 show this situation for an altitude of 400 km.

The inference from Table 2, and from similar computations at other altitudes, is that the largest accessible zenith angle is not a strong function of latitude, at least between 40°N and 40°S.

The azimuths in which the largest accessible zenith angles occur are, however, a strong function of latitude, with a marked tendency for the largest zenith angles to be found at azimuths to the equatorward of west, as shown in Figure 1.

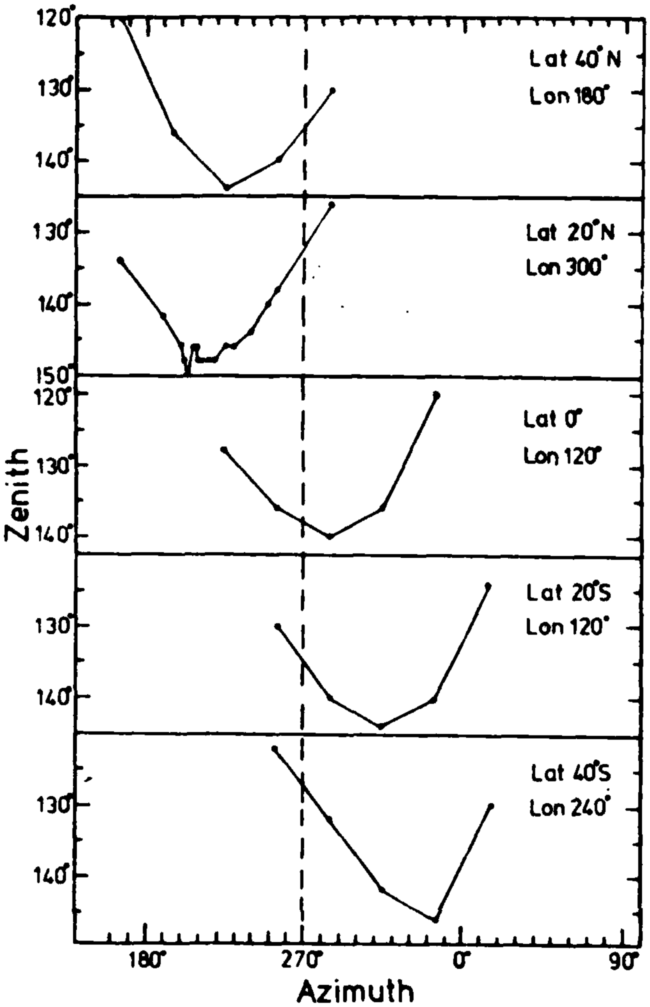

Figure 1. The variation with latitude and azimuth of largest accessible zenith angle for a satellite orbiting at 400 km altitude. The longitudes chosen are those for which the accessible zenith angle was largest for each latitude.

Conclusion

Satellites in earth orbit at medium altitudes with orbital inclination of 40° or less may easily be reached by primary cosmic ray particles from zenith angles well below that of the local geometric horizon. At altitudes of 1250 km and above particles can reach the satellite from all possible zenith angles.

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HYDRA — The New Observing Environment at the Parkes Radio Telescope

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Introduction

After 21 years the Parkes radio telescope has undergone a major refit. A new VAX-11/750 running VMS has replaced the aged Digital Equipment Corporation PDP-9 computer. Other new equipment includes two systems not previously available — the Mk II RING communication system (Willing and Ables 1983) and the 'observer workstations'.

A new observing system, called HYDRA, has been developed to enable the general user to make the best use of the new facilities.

Specification of HYDRA

Two extreme approaches could be taken when designing such a system:

(a) The piecemeal approach — one simple program working in complete isolation for each type of observation.

(b). The 'integrated' approach, in which the hardware and each of the simple programs are linked into a complete environment for performing astronomical observations.

It is neither desirable nor practical to design a single monolithic observing program to control the whole range of observations that are performed at Parkes. A continuum scanning program and a program for collecting pulsar data, for example, have quite different requirements.

The design of HYDRA allows individual components to be enhanced or replaced with ease. To this end we have provided a software framework which permits, in a convenient and standardized manner, communication between the user, his equipment, his data files and the telescope control and receiving equipment. This framework supports software components which perform the data collection and collation, as well as post-observational processing. It is easy to add observing programs and post-observational processing programs to this well-defined framework (as long as a number of ground rules are observed).

The following requirements were taken into consideration during the design.

(a) Observers often wish to analyse data immediately; they should be able to continue observing while this is being done.

(b) Each of the observing programs should have the same user interface. This interface should be provided via a menu system in which all of the data input to the observing program are specified. The menu system should be many-layered, allowing the user to control the various parts of the system separately. A help facility should be provided to explain the function of that layer, and to

APPENDIX C.

SENSITIVITY OF COSMIC RAY TRAJECTORY CALCULATIONS TO GEOMAGNETIC FIELD MODEL REPRESENTATIONS

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2

ABSTRACT

Cosmic ray vertical cutoff rigidities at sea level have been calculated, using the trajectory-tracing method, for a number of different epochs. These calculations have been carried out for a world-wide grid of locations, and, in an effort to locate the cosmic ray equator, for a fine grid in the equatorial region. Comparison of the vertical cutoff rigidity values obtained using the International Geomagnetic Reference Field model for 1980.0 with those obtained from previous models shows systematic significant changes in the Atlantic Ocean region and over South America. The differences are greater than those predicted utilizing the older field models with their predicted secular change. The cutoff rigidity values calculated using the new IGRF 1980.0 field model appear to be in better agreement with data from cosmic ray latitude surveys in the Atlantic Ocean region. The changes in the cosmic ray equator are asymmetrical with essentially no changes in the equator position in the Asian and Pacific region, but with significant changes in the South American, Atlantic Ocean and West African regions. Calculations have also been undertaken for different directions of arrival for a satellite orbiting at 400 km altitude using the predicted 1980 field model and the interim 1980 field model adopted in 1981. Some differences have been found.

1. INTRODUCTION

The cutoff rigidity is a concept which describes the magnetic shielding provided by the geomagnetic field against the arrival of charged cosmic ray particles. Rigidity is a specialized term, momentum per unit charge, that describes the curvature of the path of a charged particle traversing the geomagnetic field. It is a unit independent of particle species or nuclear composition, which can be converted to an energy for any specified charged nuclei. The cutoff rigidity of any geographic location is a function of both the zenith and azimuth angles of arrival. At the surface of the earth and in the vertical direction, the cutoff rigidity has a value of ~13 to ~18 GV at the cosmic ray equator and is theoretically zero at the magnetic poles. In actual practice this geomagnetic cutoff is, in general, not sharp and in more technical terms we use 'upper computed cutoff' a rigidity above which all particles are allowed in the specified direction, 'lowest computed cutoff', a rigidity below which no particle has been computed to arrive from the specified direction, and an 'effective cutoff' accounting for the relative transparency of the cosmic ray penumbra (Shea *et al.*, 1965).

The general equation of particle motion in the magnetic field does not have a solution in closed form even in a simple dipole field. To determine which rigidities are allowed at a specified geographical location and direction of particle arrival, it is necessary to perform detailed and extensive numerical calculations of cosmic ray trajectories in a mathematical model of the earth's magnetic field. To accurately determine the cutoff rigidity of a specified location on the earth in a specified direction, cosmic ray trajector- [illegible] ively been calculated until a rigidity is reached [illegible] are forbidden at that location and direction.

Estimates of cutoff rigidities obtained from trajectory calculations were first published by Freon and McCracken (1962). A considerable number of such cutoff rigidities have subsequently been calculated (Shea and Smart, 1982, and references therein).

The aim of these calculations has generally been to obtain a parameter suitable for the ordering of data from cosmic ray detectors, either mobile or stationary, on or close to the surface of the earth. The cutoffs obtained should refer to the epoch in which the data were obtained, and for this reason, and also for the purely practical reason of availability of field models, cutoffs have been calculated at one time or another with most of the field models which have been available, including those of Finch and Leaton (1957), Jensen and Cain (1962), and IGRF models for 1965.0 (IAGA Commission 2, Working Group 4, 1969), 1970.0, 1975.0, and 1975.0 projected forward to 1980.0 (IAGA Division 1, Study Group, 1976) and 1980.0 (Peddie, 1982).

2. METHOD

To specify the exact path of a charged particle in the geomagnetic field it is necessary to numerically integrate the differential equation of motion

$$(\ddot{\underline{r}} = \frac{q}{m} \dot{\underline{r}} \times \underline{B})$$

along the entire trajectory from its commencement point. In principle any numerical integration technique may be used. Due to the complex trajectories of a number of the cosmic ray particles with which we are concerned, we have standardized on the use of the fourth order Runge-Kutta integration technique.

as originally described by McCracken *et al.*, 1962. For practical reasons we calculate the trajectory of a negatively charged particle moving outward from the earth at a particular direction from a specific location. Such a trajectory is identical to that of a positively charged particle of equal rigidity approaching the location from the same direction, although traversed in the opposite direction.

Each of the cutoff rigidity values was calculated in the same manner by initiating the cosmic ray trajectory at the top of the sensible atmosphere (for this purpose an altitude of 20 km above the surface of the earth) in the vertical direction. The calculations were continued until either access to the interplanetary medium was assured (the trajectory extended to a distance of more than 25 earth radii) or the trajectory was found to be forbidden. Forbidden trajectories were divided into two groups, those which intersected the solid earth (called re-entrant trajectories) and those for which no solution could be obtained within a reasonable number of iterations arbitrarily selected at 200,000. Trajectories of the latter type are generally found only at locations at high geomagnetic latitudes. They do not form a significant fraction of the results reported here.

3. WORLD GRID OF VERTICAL CUTOFF RIGIDITY VALUES

The effective vertical cutoff rigidities calculated for a world grid (Shea and Smart, 1983) utilizing the 10th order and degree IGRF model for Epoch 1980.0 (Peddie, 1982) are illustrated in Figure 1. Actual cutoffs were calculated for an altitude of 20 km for increments 5° in latitude and 15° in longitude between [illegible]°S and 80°N latitudes. Multi-variate interpolation was used to determine cutoffs on a 1° by 1° grid from which the plotted contours were obtained. Significant differences have been found between the effective vertical cutoff rigidities calculated for Epoch 1965.0 and those calculated for Epoch 1980.0 Changes of the order of ±0.10 GV were calculated for many areas of the world. Major increases were calculated for the North Atlantic Ocean area, and major decreases for the South Atlantic Ocean and South American areas, as illustrated in Figure 2.

4. THE COSMIC RAY EQUATOR

When it became practical to calculate vertical cutoff rigidities by the trajectory-tracing technique it also became feasible to locate the maximum in the vertical cutoff rigidity as a function of latitude at a given longitude, thereby determining the location of the cosmic ray equator by theoretical methods (Shea,1969). We have determined the cosmic ray equator for Epoch 1980.0 in the following manner. Vertical cutoff rigidities were calculated at intervals 1° in latitude and 5° in longitude in the region of the cosmic ray equator. These calculations were made for approximately 10 discrete latitudes at each longitude centred around the location of the equator determined for previous Epochs (Shea and Smart,1975). The maximum vertical cutoff rigidity for each longitude was determined by a least squares fit to the vertical cutoff rigidities along each longitudinal meridian, with the loci of these points defining the cosmic ray equator. The location of the cosmic ray equator for epoch 1980.0 and that determined in a similar manner for epoch 1955.0 are shown in Figure 3. The cosmic ray equator for Epoch 1980.0 has shifted northward by more than 1° in latitude between longitudes 280°E to 360°E with a maximum shift of slightly more than 4° in latitude between longitude λ 310°E and 325°E. The [illegible] shift in the cosmic ray equator in the past 25 years is asymmetric and confined to the South American and Atlantic Ocean areas.

This shift in the location of the cosmic ray equator is consistent with the results of Sporre and Pomerantz (1970) who reported finding a similar shift by experimental measurements along longitude 346°. Other experimental measurements conducted over the past 45 years, mostly in the Pacific Ocean area, are consistent with the results shown in Figure 3, that there has been no significant variation in the position of the cosmic ray equator in those longitudes.

5. TRAJECTORY CALCULATIONS FOR SATELLITE ALTITUDES

In addition to the calculations reported in previous sections we have also computed a very extensive set of cutoff rigidities for points on the shell traversed by an earth satellite in a circular geocentric orbit at a mean altitude of 400 km. A total of 67 directions of particle arrival were considered at each of 132 locations distributed each 10° in latitude and 30° in longitude around the orbital surface, extending in latitude between 50°N and 50°S. Some initial results have been reported (Humble *et al.*, 1979) and a more detailed report is currently being prepared. The calculations were commenced in 1977, initially in connection with experiments to be flown on board the HEAO-C spacecraft. A field model for epoch 1980.0 was required, and the IGRF 1975.0 model was chosen, extrapolated forward to 1980.0 by use of the associated secular drift coefficients (IAGA, 1976, *op.cit.*). This field model is of 8th order and degree.

Following the adoption of the present IGRF for 1980.0 (Peddie, 1982) we carried out some sample tests to determine, in a qualitative fashion, the effect on our results of changing from the model previously used to the adopted

1980.0 model. Due to the amount of computer time involved we were anxious to avoid a more comprehensive comparison unless such were forced upon us by the results of the pilot study.

A further complication exists, induced by the decision to define the adopted 1980.0 model at 10^{th} order and degree. Trajectory integration uses large amounts of computer time, a considerable fraction of which is utilised in evaluation of the vector components of the geomagnetic field. The integration technique used (section 2) requires these magnetic field vectors to be computed four times per integration step. The computer time required for each computation of vectors increases by approximately the square of the degree and order of the field model used, and the change from 8^{th} to 10^{th} order and degree increases the computation time for a given trajectory by about 25%. (That this is less than the expected value is partly accounted for by our dropping the higher order terms in the expansion when they become insignificant at increasing altitude.) We have therefore also undertaken a qualitative survey on the effect of truncating the adopted model at 8^{th} order and degree.

In this study we have compared cosmic ray cutoff rigidities calculated for 66 locations on our world-wide grid using

(1) the 8^{th} order and degree IGRF 1975.0 extrapolated forward to 1980.0 (abbreviated as X08 in the following discussion).

(2) the 10^{th} order and degree IGRF 1980.0 adopted field model truncated to 8^{th} order and degree (abbreviated as A08), and

(3) the adopted 10^{th} order and degree IGRF 1980.0 (Peddie,1982) abbreviated as A10.

The results are tabulated in table 1.

Inspection of table 1 shows significant differences between the results obtained using the various models. The rigidity intervals used were 1% throughout, abnormally coarse compared with many investigations, but it is clear even at this interval that the choice of field model is critical in some circumstances.

Another set of calculations display sensitivity to choice of field model. Charged particles are able to reach orbiting satellites from generally westerly directions at zenith angles considerably larger than that of the local earth horizon. We have carried out calculations to determine the largest zenith angles with which such particles are able to reach a satellite orbiting at 400 km (Humble *et al.*, 1983). A sample of the results obtained using the adopted 10^{th} order field is shown in figure 4a. In figure 4b we show the differences from the A10 field results obtained by use of the X08 and A08 models. The majority of the differences are 2°, equal to the zenith angle increment used.

The implication of our results is that the choice of field model is important, even at the relatively coarse sampling intervals in rigidity and direction of arrival which have been employed. However, it should be noted that this is a general statement, which does not apply to all trajectories. In many cases individual trajectories are rather similar regardless of the field model used. Figure 5 shows altitude vs longitude sections for such a trajectory calculated, for the same initial conditions, in all three field models. There is very little significant difference between the three sections - the 'typical' result.

For certain trajectories, however, the choice of field model is crucial. Figures 6 and 7 depict this situation for two different sets of initial conditions. The figures show totally different trajectories in each of the field models. The figures are presented for illustrative purposes only, as an indication of what differences can be found, and it should not be concluded from them that such differences would necessarily be found over a range of other initial conditions. We note, however, that these trajectories pass through the Atlantic region longitudes to which reference has been made in section 3.

6. DISCUSSION AND CONCLUSION

In the past few years it has become more apparent that the cosmic ray trajectory calculations used in the analyses of cosmic ray observations must be made utilizing geomagnetic field models for the epoch in which the data were obtained. The general secular trend that has become apparent over the past 25 years is sufficiently large to be detectable in precise cosmic ray measurements. Furthermore, it would seem that the IGRF for Epoch 1975.0 and its associated predicted time derivatives is particularly ill-suited for the analysis of cosmic ray data acquired in the longitude embracing the Atlantic Ocean region.

As shown in Figure 2b, major changes are found between the vertical cutoff rigidities calculated for the world grid for Epochs 1965.0 and 1980.0 in the Atlantic Ocean region. This is the same longitudinal region where we have found significant differences between cutoff rigidities computed for 1980 using initially predicted and later more definitive 1980 magnetic field models. This is also the area where latitude surveys have shown the greatest deviation from the results expected on the basis of model calculations (Mischke *et al.*, 1977 or 1979; Shea *et al.*, 1981) and where there is a major latitudinal shift in the cosmic ray equator over a 25-year period.

We note that regions in which we find major changes with time in cosmic ray trajectories and cutoff rigidities are similar to those regions in which the horizontal component of the magnetic field shows temporal variations (Peddie, 1982). Cosmic ray particles respond to the integral of $\underline{V} \times \underline{B}$ over their entire path length in the geomagnetic field. Cosmic ray trajectories having rigidities near the cutoff have a larger fraction of their trajectories at lower altitudes and are therefore more likely to be affected by the higher order components that contribute to the total geomagnetic field topology.

ACKNOWLEDGEMENTS

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Mischke.C.F.W.. Raubenheimer.B.S.. Stoker.P.H.. van der Walt.A.J.. Shea.M.A. and Smart.D.F.. 1979. Experimental observations of secular changes in the vertical cutoff rigidity. 16th International Cosmic Ray Conference. Conference Papers. 4:279-284.

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Shea,M.A., Smart,D.F., Stozhkov,Y.I., Svirzhevsky,N.S., Svirzhevskaya,A.K., Basilevskaya,G.A. and Charackchyan,T.N., 1981. Analysis of cosmic ray intensity data and trajectory calculated vertical cutoff rigidities for the latitude survey made during the 22nd Soviet Antarctic Expedition. 17th International Cosmic Ray Conference, Conference Papers. 4:213-216.

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Longitude	0		60		120		180		240		300	
Field	X08	A08	X08	A08	X08	A08	X08	A08	X08	A08	X08	A08
Latitude												
50°N		-2		0		0		0		-4		0
40°N	-2	0	+3	0	0	0	0	0	-2	0	-6	-5
30°N	+1	0	0	0	+1	0	0	0	+4	0	+2	+2
20°N	0	0	+1	0	0	0	0	0	+1	0	+3	0
10°N	0	0	+1	0	0	0	0	0	-1	0	+1	+1
0	0	0	0	0	0	0	0	0	0	0	0	0
10°S	+1	0	-1	0	0	0	-1	0	0	0	0	0
20°S	-1	-2	-3	0	0	0	0	0	0	0	0	0
30°S	-3	0	-2	0	-2	0	0	0	+1	0	+1	0
40°S	+1	-1	-3	-3	+6	0	+1	0	0	+1	+3	+2
50°S		-4		0				0		-1		+5

Table 1. Vertical upper computed cutoff rigidities calculated using the extrapolated (X08) and truncated adopted (A08) geomagnetic field models expressed as a percentage difference from the cutoff calculated for the 10th order and degree adopted (A10) field.

FIGURES

Figure 1 Estimated vertical cutoff rigities, epoch 1980.0 The contours are in units of GV.

Figure 2 Contours of averaged annual change of estimated vertical cutoff rigidity between 1965.0 and 1980.0

Figure 3 Estimated geographic location of the cosmic-ray equator for epochs 1955.0 and 1980.0.

Figure 4a Largest zenith angles at which charged primary particles are able to reach a satellite orbiting at 400 km altitude. IGRF 1980.0 adapted to 10th order field.

4b The largest accessible zenith angles found using other field models, expressed as a difference from the results shown in Figure 4a. The abbreviations used are defined in the caption to table 1.

Figure 5 Trajectories of 15.844 GV particle arriving at (lat.0°, long.120°, alt.400km) from zenith 128°, azimuth 225°.

Figure 6 Trajectories of 9.828 GV particle arriving at (0°, 300°, 400km) from (128°, 1[illegible]°). Note that the arrival direction is accessible from infinity [illegible] the A08 and X08 field models but is inaccessible (trajectory forbidden) in the A10 field.

Figure 7 Trajectories of 10.537 GV particle arriving at 0°, 60°, 400km) from (132°, 225°). The direction of arrival is forbidden from infinity in both the A08 and A10 fields, but is accessible according to the earlier (X08) model.

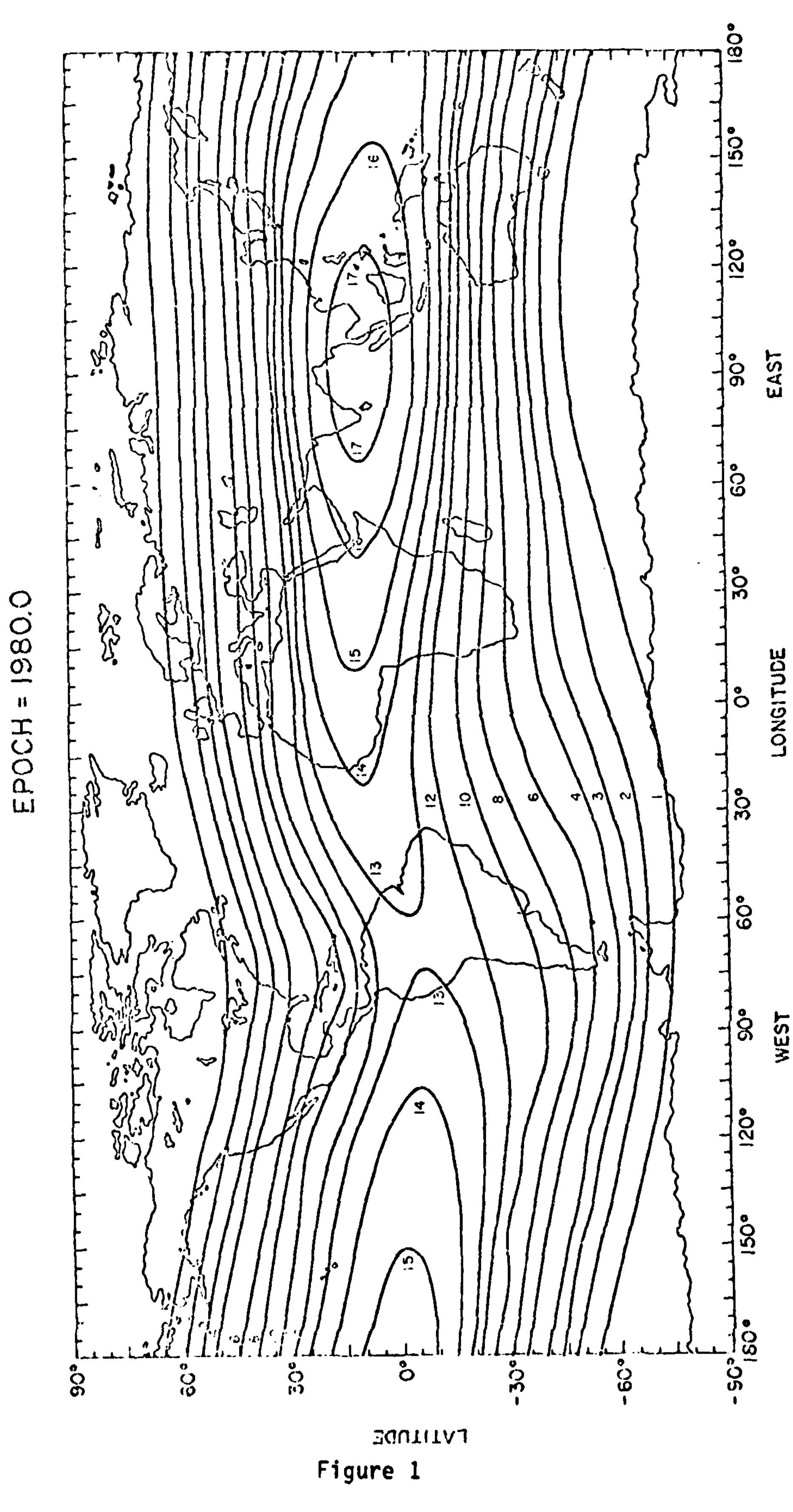

EPOCH = 1980.0
LATITUDE
90°
60°
30°
0°
-30°
-60°
-90°
LONGITUDE
180°
150°
120°
90°
60°
30°
0°
30°
60°
90°
120°
150°
180°
WEST
EAST
1
2
3
4
6
8
10
12
13
14
15
16
17

Figure 1

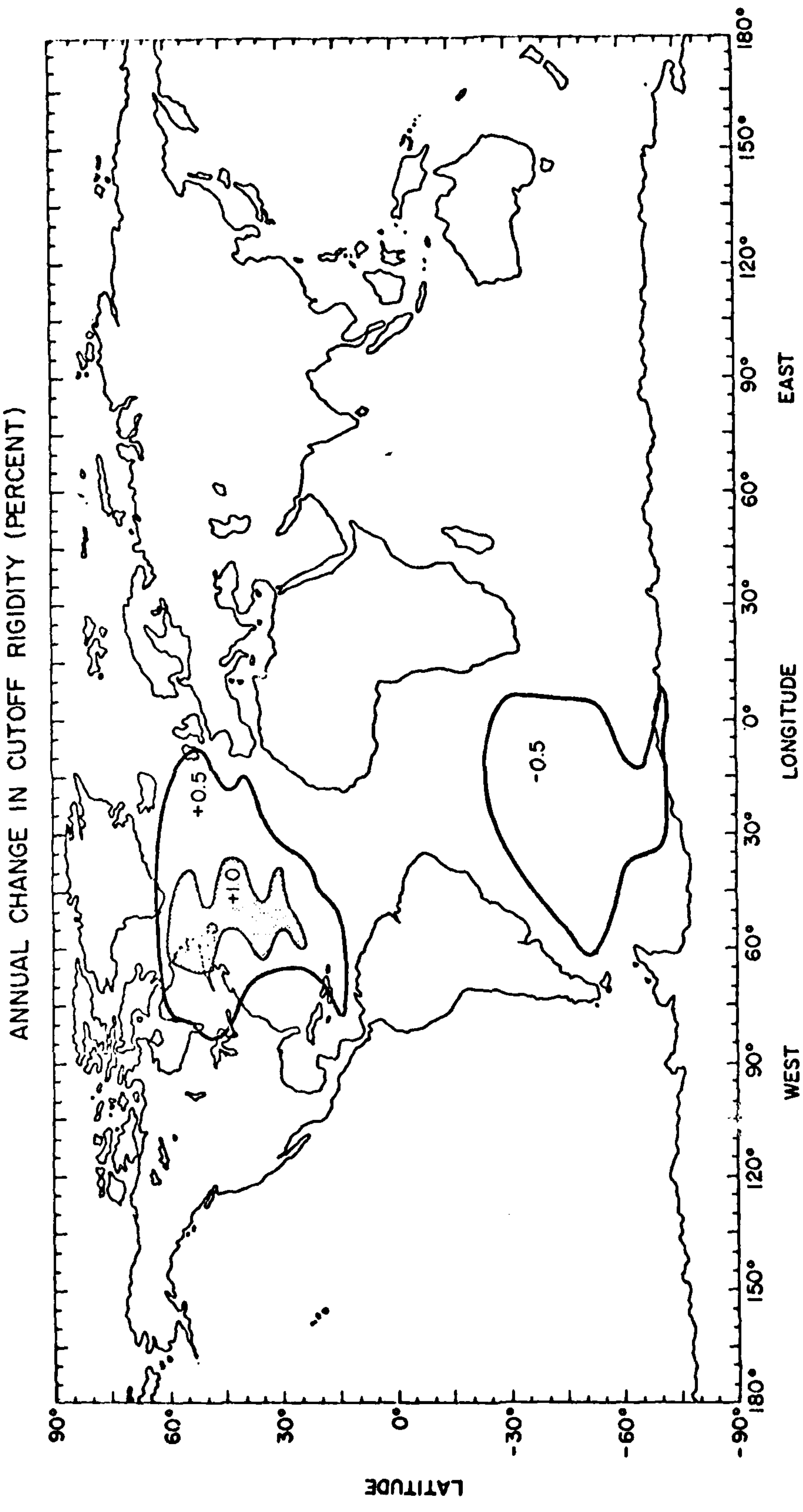
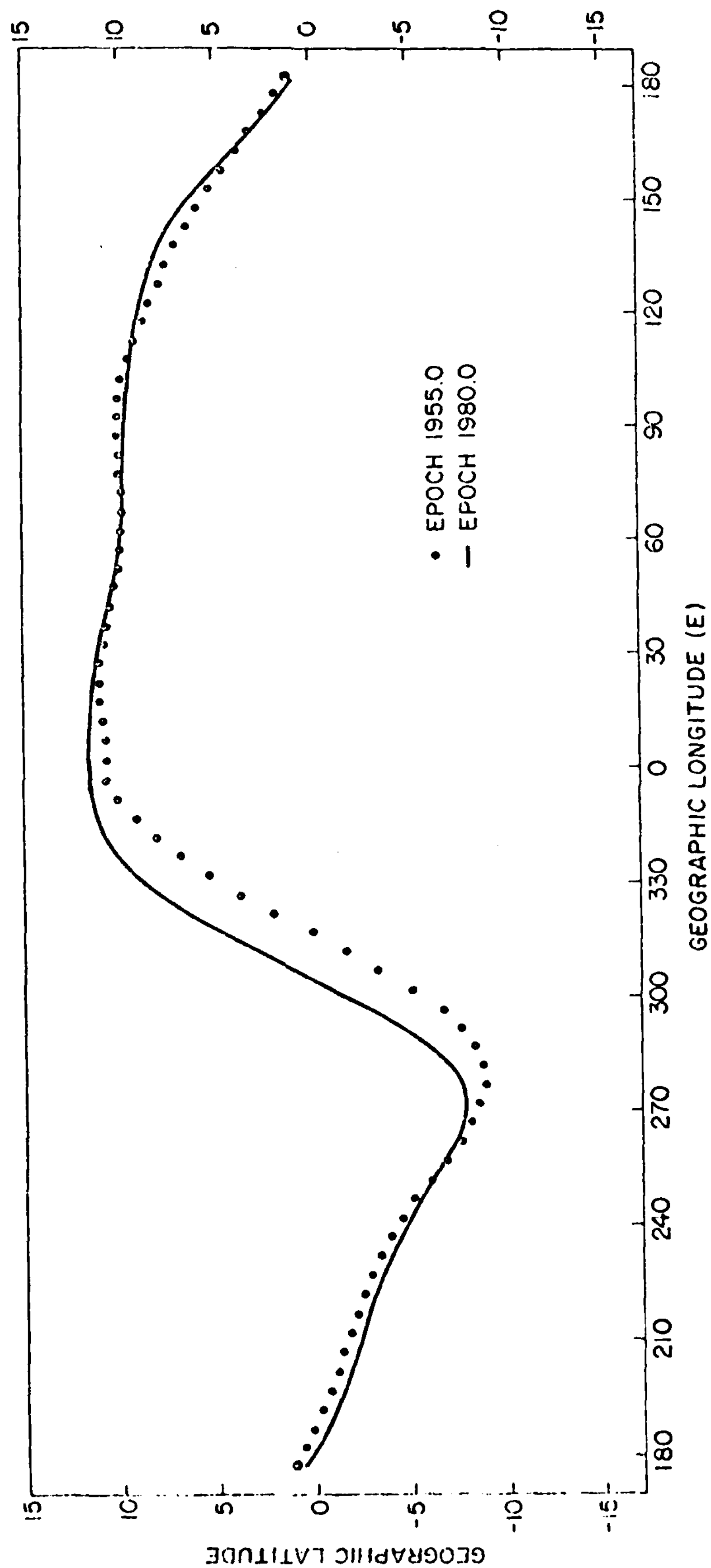

ANNUAL CHANGE IN CUTOFF RIGIDITY (PERCENT)
LATITUDE
90°
60°
30°
0°
-30°
-60°
-90°
LONGITUDE
WEST
EAST
180°
150°
120°
90°
60°
30°
0°
30°
60°
90°
120°
150°
180°
+0.5
+1.0
-0.5

Figure 2



EPOCH 1955.0
EPOCH 1980.0
GEOGRAPHIC LONGITUDE (E)
GEOGRAPHIC LATITUDE
180
150
120
90
60
30
0
330
300
270
240
210
180
15
10
5
0
-5
-10
-15

Figure 3

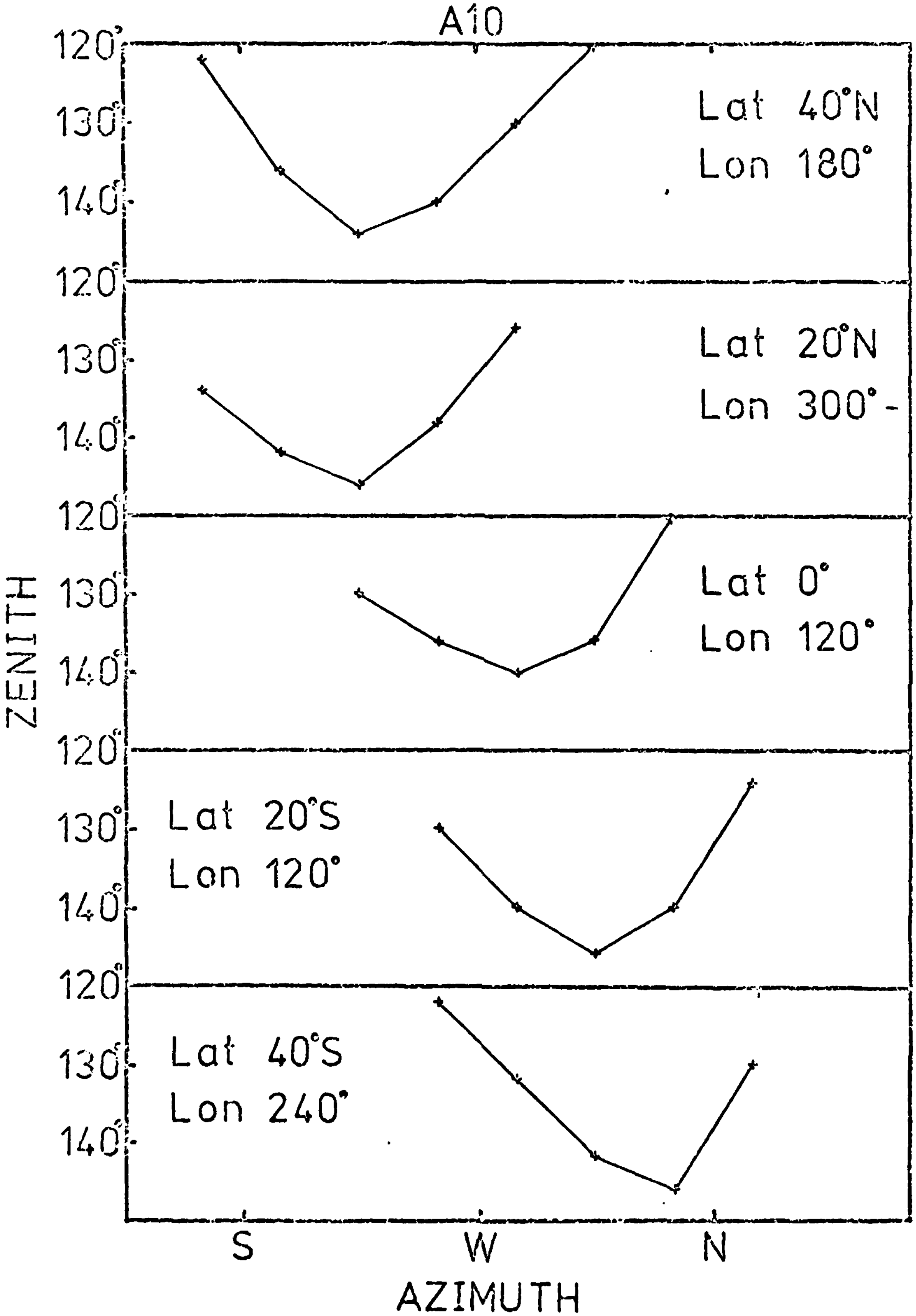

A10
120°
130°
140°
Lat 40°N
Lon 180°
120°
130°
140°
Lat 20°N
Lon 300°
120°
130°
140°
Lat 0°
Lon 120°
120°
130°
140°
Lat 20°S
Lon 120°
120°
130°
140°
Lat 40°S
Lon 240°
ZENITH
S
W
N
AZIMUTH

Figure 4a

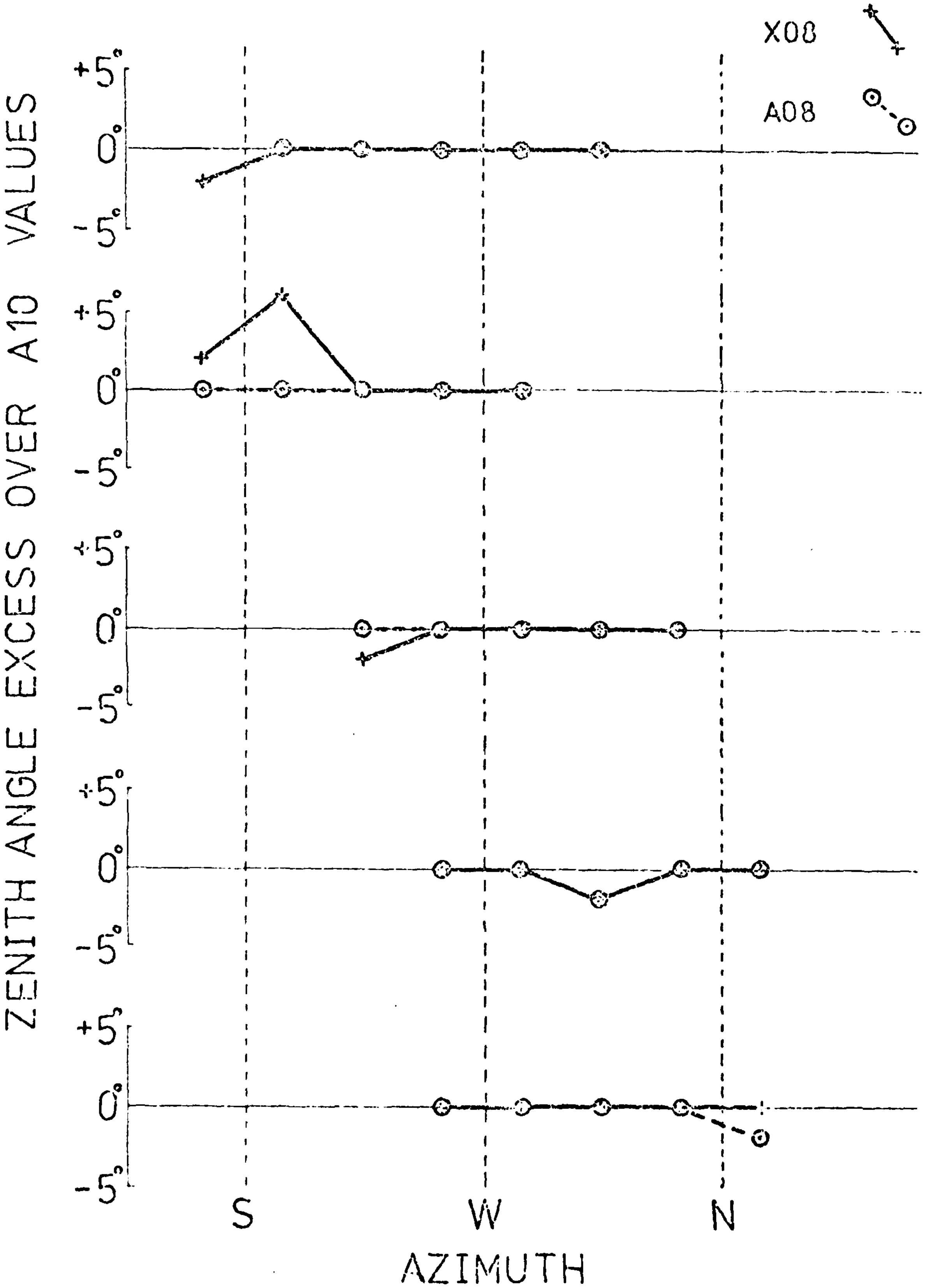


Figure 4b

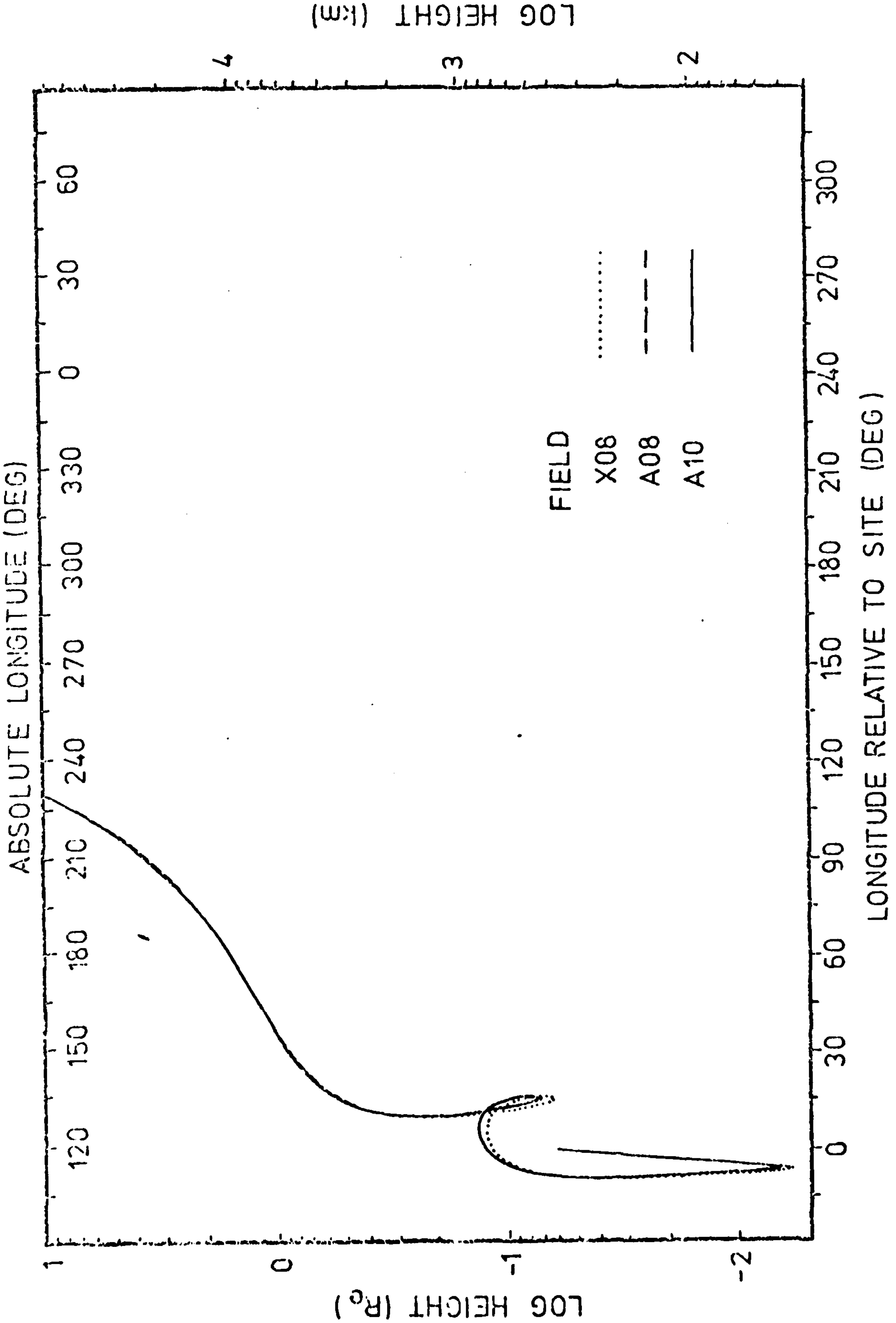

LOG HEIGHT (km)
ABSOLUTE LONGITUDE (DEG)
LONGITUDE RELATIVE TO SITE (DEG)
LOG HEIGHT ($R_{\odot}$)
FIELD
X08
A08
A10

Figure 5

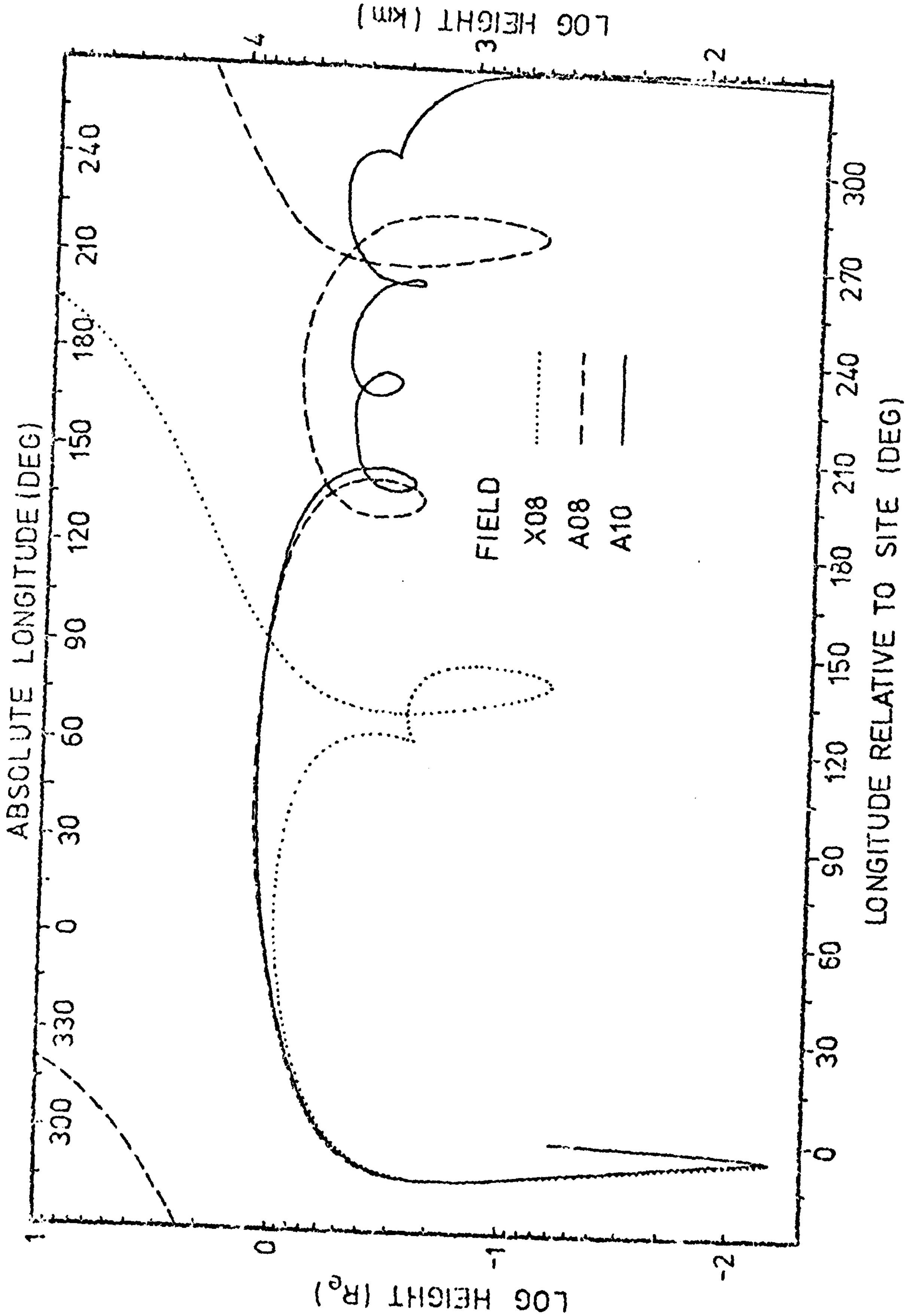

ABSOLUTE LONGITUDE (DEG)
LONGITUDE RELATIVE TO SITE (DEG)
LOG HEIGHT (km)
LOG HEIGHT (R_e)
FIELD
X08
A08
A10

Figure 6

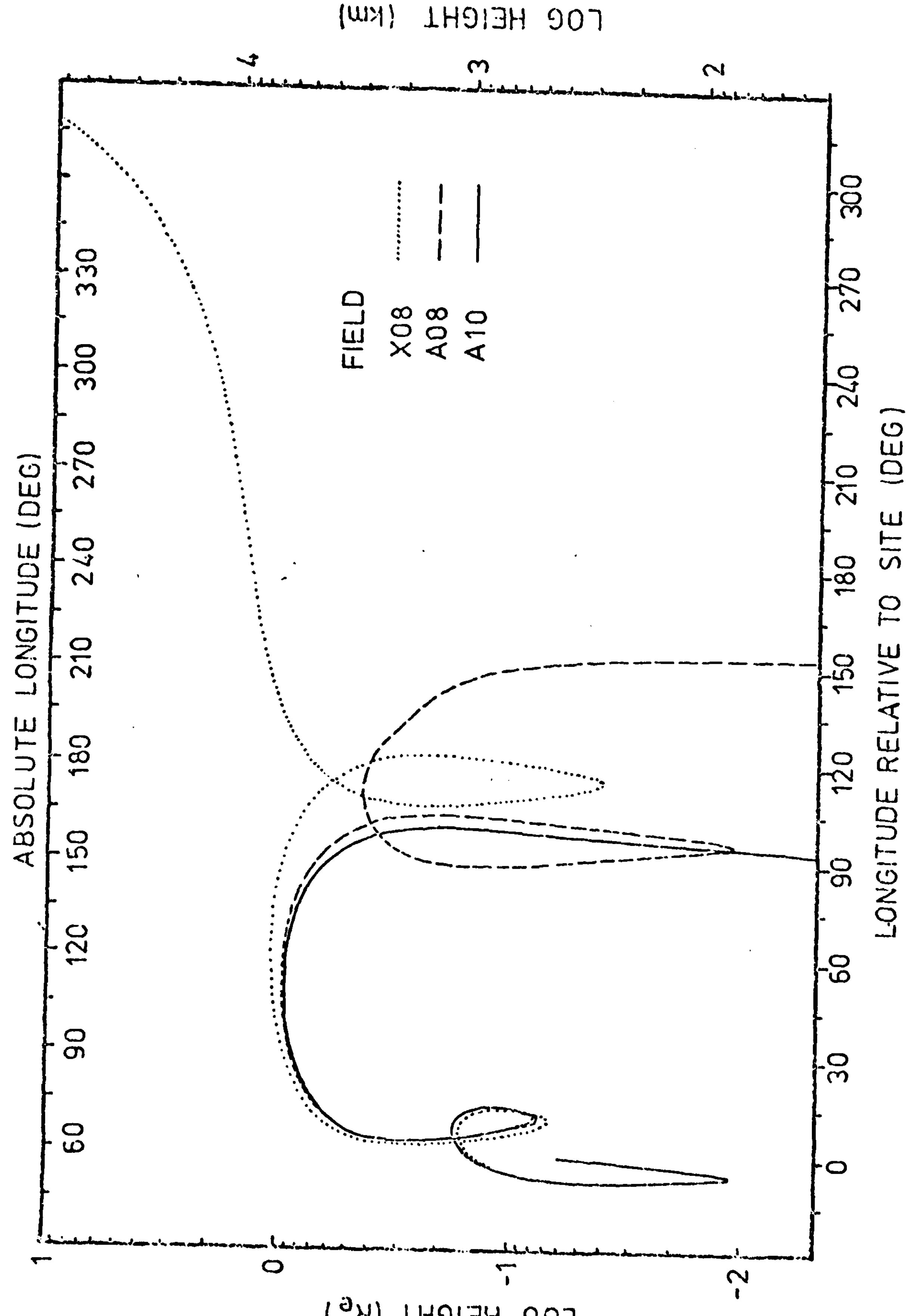

LOG HEIGHT (Km)
4
3
2
ABSOLUTE LONGITUDE (DEG)
60
90
120
150
180
210
240
270
300
330
FIELD
X08
A08
A10
LONGITUDE RELATIVE TO SITE (DEG)
0
30
60
90
120
150
180
210
240
270
300
1
0
-1
-2
LOG HEIGHT (R_e)

Figure 7

APPENDIX D.

Hits Below the Belt - Cosmic Ray Direct Access to Low Altitude Satellites from Earthward Directions

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ABSTRACT

We have previously reported finding that primary cosmic ray particles are able to reach satellites at 400 km altitude from zenith angles up to 135°. More detailed investigations have now found that access is possible at certain locations at zenith angles up to 150°, only 30° from the nadir. Access from zenith angles of order 140° to 144° is common and occurs at all the latitudes which we have investigated between 40° North and 50° South. Particles arrive at these large zenith angles from azimuths on the equator side of west in both hemispheres.

Presented at the Fall meeting of the American Geophysical Union, San Fransisco, CA, December 1982.

The Directions from which Cosmic Rays may Reach Earth Satellites

by HUMBLE, J.E., UNIVERSITY OF TASMANIA

It is easy to feel intuitively that primary cosmic rays are able to reach earth satellites from all directions above the horizon and will be unable to do so from directions much below the horizon. The falsity of the latter assumption is discussed, and it is shown that primary particles can reach satellites at 400 km altitude from zenith angles up to 150°. At an altitude of 1250 km primaries may gain access to the satellite from zenith angles up to at least 178°, essentially from directly beneath the satellite.

Presented at the annual meeting of the Astronomical Society of Australia, Sydney, N.S.W., Australia, May 1983.

FIELD MODEL COMPARISONS: COSMIC RAY DIFFERENCES BETWEEN THE PREDICTED AND ADOPTED 1980.0 FIELDS

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Cosmic ray trajectories have been calculated using the 10th order definitive geomagnetic reference field adopted at the 1981 IAGA meeting in Edinburgh; the same field arbitrarily truncated to 8th order; and the Interim Geomagnetic Reference Field for 1980.0, based upon the published 1975.0 field and its associated secular drift coefficients. It is shown that in the majority of cases the trajectories obtained using each field model are rather similar. However, in certain circumstances considerably different trajectories result, particularly if the location concerned is near to the South Atlantic Geomagentic anomoly. The use of the different field models does not significantly alter the largest accessible zenith angles calculated for some sample locations.

Presented at the XVIII General Assembly of the International Union of Geodesy and Geophysics, International Association for Geomagnetism and Aeronomy meeting, Hamburg, Federal Republic of Germany, August 1983.

COSMIC RAY ACCESS TO SATELLITES FROM LARGE ZENITH ANGLES

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ABSTRACT

As the altitude of earth-orbiting satellites increases it becomes progressively easier for primary cosmic-ray particles to gain access to them from directions below the geometric horizon. Results are presented from a comprehensive survey of the largest accessible zenith angles for a range of altitudes and geographic locations. The search has disclosed that primary particles are able to reach a satellite at an altitude of 1250 km from zenith angles as large as 178°.

Presented at the 18th International Cosmic Ray Conference, Bangalore, India, August 1983.

Cosmic Ray Access to Spacecraft from Earthward Directions:
the Role of the Atmosphere

J.E.Humble
Physics Department, University of Tasmania

Previous calculations on this topic have used a very simple model for the atmosphere. The model assumed the atmosphere to be totally transparent to cosmic rays at altitudes above 30 km and totally opaque to them at lower altitudes. The calculations reported here use a realistic model atmosphere. It is shown that the results obtained are similar to those obtained with the cruder model.

Presented at the annual meeting of the Astronomical Society of Australia,
Coonabarabran, N.S.W, Australia, May 1984.

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